MARQUIS

Influence of the Form
Of Steam Nozzles on the
Velocity of the Jet

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EXPERIMENTS ON THE INFLUENCE OF THE FORM OF STEAM NOZZLES ON THE VELOCITY OF THE JET

BY

FRANKLIN WALES MARQUIS

THESIS FOR THE DEGREE OF BACHELOR OF SCIENCE
IN MECHANICAL ENGINEERING

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The Influence of the Form of a Steam Nozzle on the Velocity of the Jet.

I

Historical Outline of the Development of the Laws of the Flow of Elastic Fluids.

Since the advent of the steam turbine the phenomena of steam flow, steam velocity, and steam impulse, have received considerable attention, both from the theoretical and experimental side. The theory is as yet, however, far from complete and satisfactory, and the experimental work is fragmentary. The theory of steam flow depends primarily on the theory of flow of elastic fluids, and a short historical sketch will aid us in appreciating the peculiar difficulties and apparent contradictions, met with in this subject.

Shortly after Galileo established the

laws of falling bodies, further experiments showed that water and other inelastic fluids followed the same law. From that the velocity of water falling thru a properly shaped orifice was equal to the velocity which a body would acquire in falling a distance equal to the head, it followed that the velocities of efflux varied as the square roots of the heads. This law was applied to elastic fluids, such as air, as well, and crude experiments were made on a bladder first filled with air, and then with water. Under the same pressure it was found that it required 25 times as long to empty the bladder when filled with water, as it did when filled with air; consequently the velocity of flow of air was considered to be 25 times that of water.

In a quaint old paper read by a certain Dr. Papin before the Royal Society in 1686, the following is stated as the general law deduced from theory and experiment. "Of different liquors flowing from an orifice bearing the same

pressure, those lighter in specie must acquire the greater swiftness, and their velocities are to one another as the roots of the specific gravities of the said liquors. As much as the sq. rt. of the specific gravity of water doth exceed the square root of the specific gravity of air, so much in proportion will the velocity of air exceed the velocity of water." This law was accepted for 115 years, and it was not until late in the 19th century that furthur experiments were made.

In 1843 St. Venant and Wantzel made the first real advance, and in their report gave the first real intimation of one of the well known results of modern experiment. They make two important statements.

(1) When the pressure which acts in an opposite direction to the flow of the gas descends below three fifths of the pressure which causes the flow, the efflux instead of increasing, diminishes.

(2) A gas cannot flow into a vacuum, whatever be its pressure.

These two conclusions so apparently opposed to all reason, were too much for the experimenters, and after a second series of experiments St. Venant says, "Our experiments have proved that those singular results have no more reality than they had of probability." As late as 1846 Prof. Graham of the Royal Society announced that his experiments left no doubt as to the truth of the general law that different gases pass thru minute apertures in times which are inversely as the square roots of their specific gravities. Experimenting and investigating along the same line in 1847, Mr. William Froude, M. Inst. C. E., developed a theory of flow by which he proved that elastic fluids under pressure cannot flow into a perfect vacuum. His method of experiment was similar to that of St. Venant, Wantzel, and Graham. From 1854 to 1862 Prof. Thomson and Dr. Joule made a series of experiments on the flow of air, to determine the velocity

thru small orifices in thin plates. In Dr. Joule's report he gives a hint of one fact which has since proved of considerable importance. He says; "I have not been able to detect any effect due to vibration of the issuing stream........ there can be no doubt that vibration constituting sound will be able to travel back thru the air rushing thru the orifice if its velocity be not greater than 1090 feet per second. I have failed, however, to discover any sensible influence from this cause on the velocity of efflux."

Robert D. Napier in 1866 was the first to state what we know now to be the actual conditions under which steam or any gas flows from a higher to a lower pressure. His important conclusion, and the one which we know to be approximately true, is, as he states it; "Steam at a pressure of two or more atmospheres will rush from a boiler thru an orifice or short tube into the air, ex-

actly at the same rate as it will into a vacuum, or into any pressure less than that of the atmosphere; and generally a gas of any given pressure will rush from one vessel into another containing a gas of half the pressure at the same rate as if there were a perfect vacuum in the recipient vessel or any intermediate pressure between a vacuum and half the pressure in the cistern, both pressures being taken from zero."

This conclusion, it is seen, had been reached by St. Venant and Watzel twenty years before, and afterwards rejected by them as absolutely impossible. At this time Napier's experiments provoked heated discussions, but nevertheless the truth of his deductions, was soon established as a scientific fact, Prof. Rankine being one of the first to refute arguments brought against it, and one of the ardent supporters of the new theory.

The German scientists Zeuner, Fliegner, and Grashof, have since developed the theory, and experimented more fully. In conclusion it may be said that at the present time the laws of the flow of gases thru orifices in thin plates are known and the theory is supported by experiment.

Briefly stated the law of flow is as follows: When a gas flows thru an orifice from a reservoir in which there exists a lower pressure, P_2, the quantity of gas passing thru the orifice continuously increases as P_2 decreases, until P_2 reaches the value $.527 P_1$ for air or $.58 P_1$ for steam. Any decrease of P_2 below this point has no effect on the quantity of gas flowing thru the orifice in a given time. In other words when the maximum flow occurs $\frac{P_2}{P_1} = .527$ for a gas, or .58 for steam. As to the laws of flow in tubes of varying cross section and the phenomena taking place in the tube itself, much uncertainty exists, and it is along this line that recent experimenters and scientists are now working.

II.

The Flow of Steam Thru a Nozzle.

In the thesis of Mr. K. G. Smith, of the class of 1905, will be found a thorough treatment of the theory of the flow of steam. However a short statement of the theory of the flow of steam thru a nozzle will be made here.

As is well known, a nozzle for water, or any other inelastic fluid, which will increase the velocity of flow, should be of a gradually decreasing cross section. This, however is not true in the case of steam or other elastic fluids. In fact here, just the opposite is true. For example let us suppose that steam passes from some pressure P_1 thru a nozzle into a lower pressure P_2. When it has reached the lower pressure, it will have expanded a certain amount, which will depend upon the difference of the pressures P_1 and P_2. If the nozzle is divergent, so that the expansion takes place in it, the velocity of the jet will be increased. However, without this di-

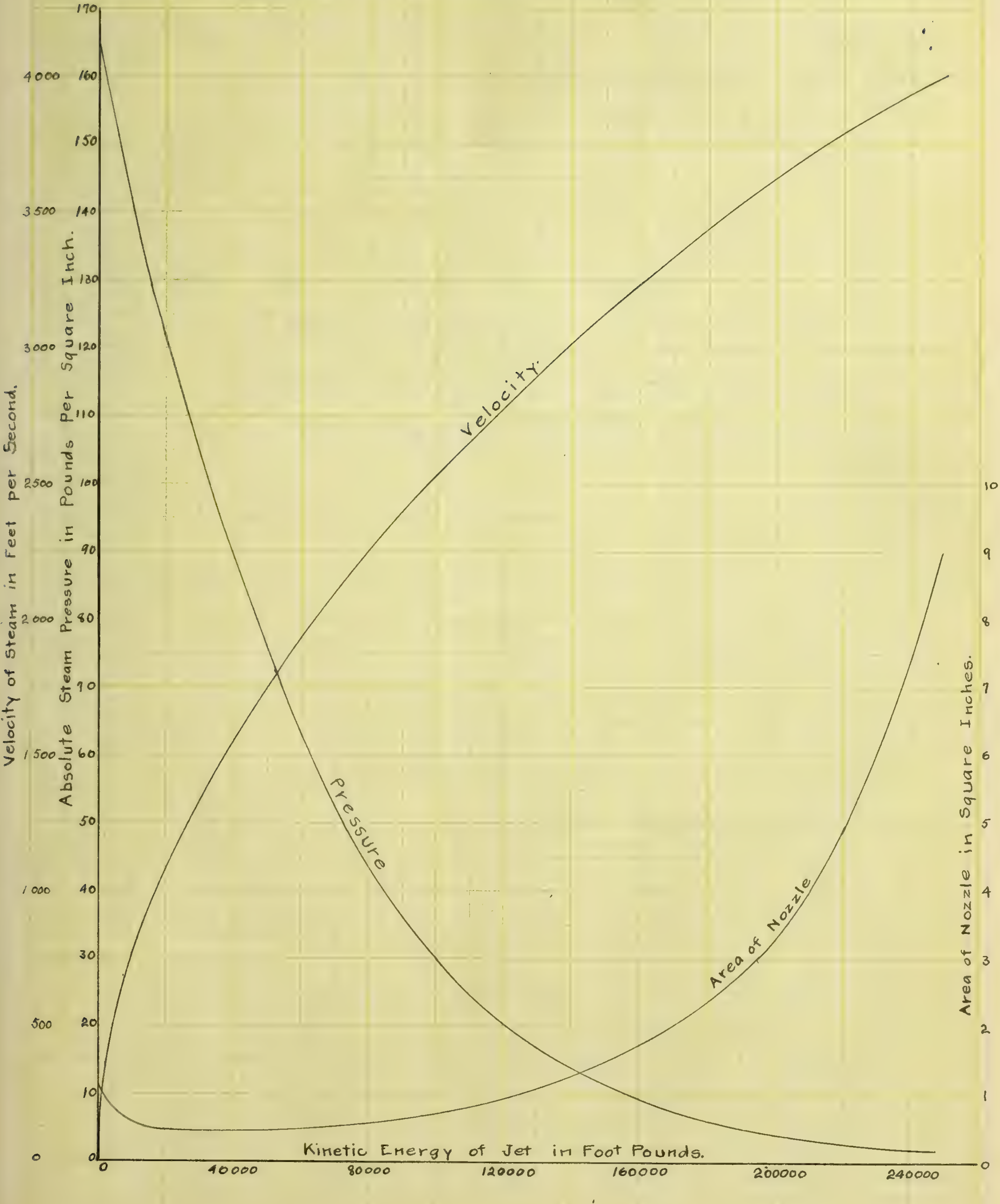
vergence, the steam will expand outside the nozzle, where it is uncontrolled by its walls, and consequently, much of the expansion will take place laterally, which will not increase the velocity of the jet. Therefore, in order to obtain the greatest possible velocity of the jet at the mouth of the nozzle, it should be divergent, and so shaped that the steam is expanded just to the back pressure P_2, at its mouth. A further reason for the divergence is apparent from the fact that the work done by the expanding steam varies nearly in direct proportion to the number of expansions, and also varies as the square of the velocity. The volume of the steam, therefore, increases much more rapidly than the velocity, and room must be provided for its proper expansion in the nozzle.

A theoretical design of a divergent nozzle, as given by Francis Hodgkinson, in paper No. 1037 of the American Society of Mechanical Engineers, will be

found on page 12. This considers a nozzle expanding 1 pound of dry saturated steam per second from an absolute pressure of 165 pounds per square inch to one pound per square inch. The assumption has been made that the expansion is adiabatic, and that equal increments of work are performed in equal increments of the nozzle length. The assumption that the expansion is adiabatic, is a logical one, as the nozzles are generally small relative to the amount of steam passing, so that there is little opportunity for any interchange of heat.

The abscissae are laid out to uniform scale, and represent the foot pounds of energy given up by the steam expanding between the limits of pressure referred to the scale of ordinates. The curve of pressure shows the pressure drop corresponding to increasing work. The velocity curve is calculated upon the assumption that all energy of the expand-

Theoretical design of a nozzle, expanding adiabatically, one pound per second of dry and saturated steam from 165 pounds absolute pressure to 1 pound absolute pressure, assuming that equal increments of work will be performed in equal increments of length of nozzle.



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ing steam has been expanded internally, and converted into velocity. The curve of the areas of the nozzle is found by the equation,

$$a = \frac{S \times x_2}{V}$$

Where a = Area of nozzle.
S = Specific volume.
x_2 = Quality of steam.
V = Velocity of steam.

III.

Experimental Determination of the Velocity of Flow of Steam Thru a Nozzle.

In the application of the flow of steam thru a nozzle to steam turbine work, the point at which the velocity of the steam is required is just where it leaves the nozzle. In looking over the reports of other experiments in this same line it was noticed that in some cases, in order to get the velocity it was necessary to estimate the density of steam at the point of efflux. This estimation depended upon temperature measurements, which were likely to be inaccurate, and seemed to be a weak point in the experiments. Moreover the velocity found by this method was merely a figure in feet per second from which the mass of steam discharged could be calculated, when the area of the orifice and the density of the steam were known. Therefore, in the present ex-

periments, it seemed desirable to measure the velocity as directly as possible, and to avoid estimating the density of steam at the point of efflux. It was therefore necessary to measure both the mass discharged and some other quantity involving the velocity. For this second quantity the impulse of the escaping jet was chosen.

Let V = the velocity of the steam, in feet per second.
W = the impulse in pounds weight.
M = the weight of steam discharged per second, in pounds.
and g = the acceleration due to gravity, = 32.16 feet per second.

Then, since the impulse of a jet of any kind is equal to the product of the mass flowing per second and the velocity of flow,

$$W = \frac{MV}{g}$$

or

$$V = \frac{Wg}{M}. \quad - \; - \; - \; - \; - \qquad (1)$$

The above formula was used in all cases in determining the veloc-

ity of the jet. It is to be noted that this formula gives the velocity at the definite point at which the impulse is measured. Thus if the steam is not fully expanded in the nozzle, it will continue to expand after leaving the nozzle, and will change in impulse and velocity. However the velocity at any point outside the nozzle may be obtained by measuring the impulse at that point.

At first an attempt was made to measure the reaction of the jet, instead of the impulse, the supposition being that the two would be the same. However, after some preliminary experiments this method was abandoned, and a method of measuring the impulse was substituted. A complete description of the apparatus used and the methods followed in obtaining the various results desired, will be found in the next section.

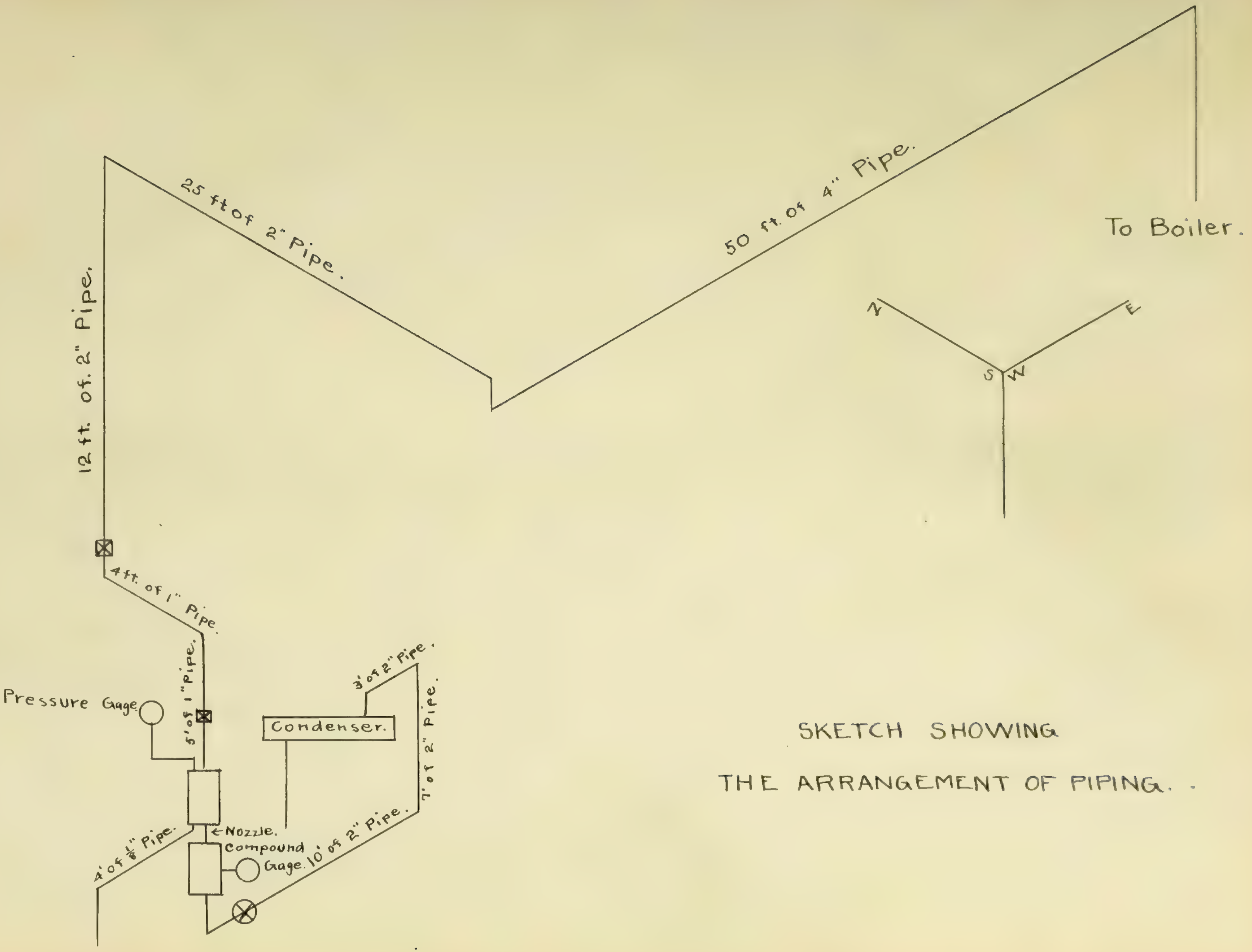
IV.

Apparatus Used and Methods Employed.

(1) In Determining the Impulse of the Jet.

The boiler which furnished the steam for the following experiments was a Babcock and Wilcox water tube boiler, which generally carried about 125 pounds pressure. A diagram of the piping leading from the boiler to the apparatus used will be found on page 18.

On page 19 will be found a diagram showing the arrangement of the apparatus used in determining the impulse of the jet. It consists of a reciver, c, into which steam was admitted by means of the one inch pipe, a. The nozzle, n, was screwed into the lower end of c. The steam was discharged from c thru nozzle n, directly against the impulse plate, d,



SKETCH SHOWING
THE ARRANGEMENT OF PIPING.

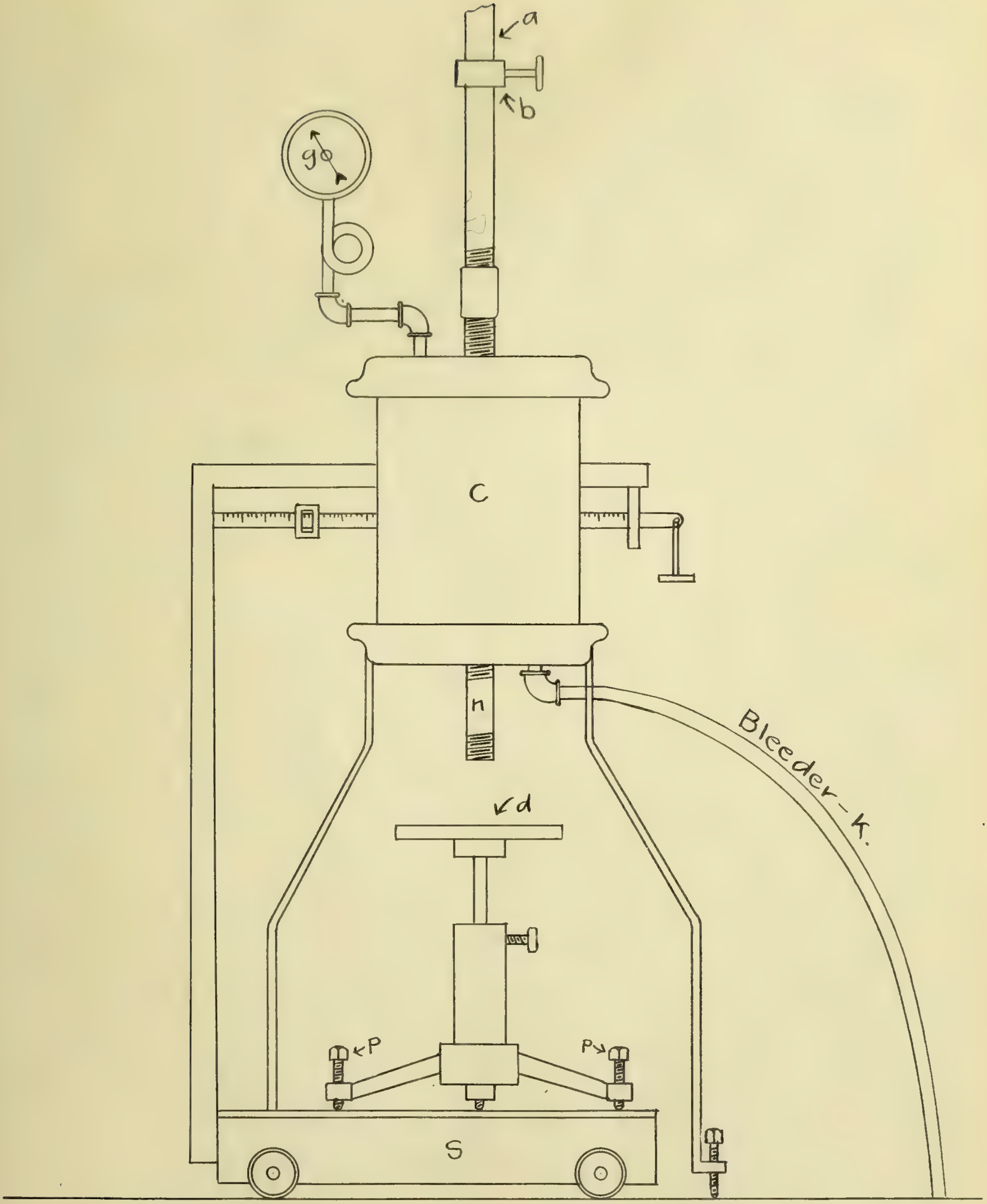
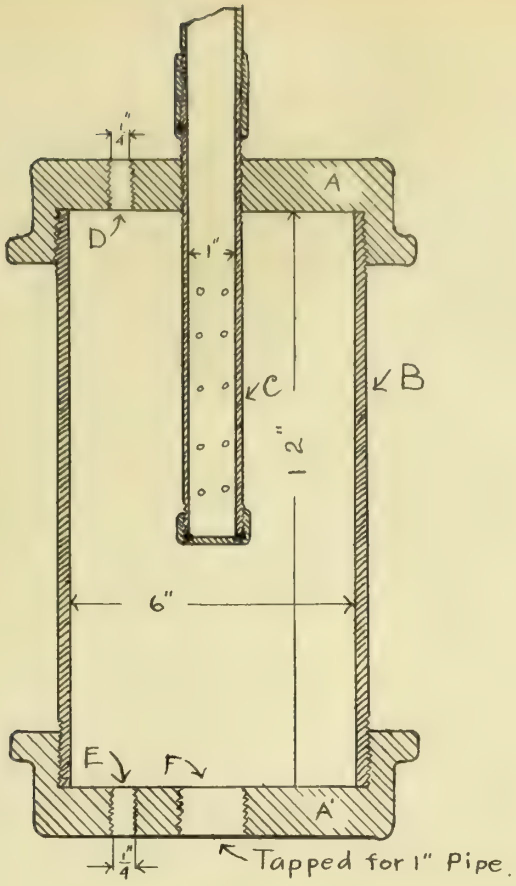


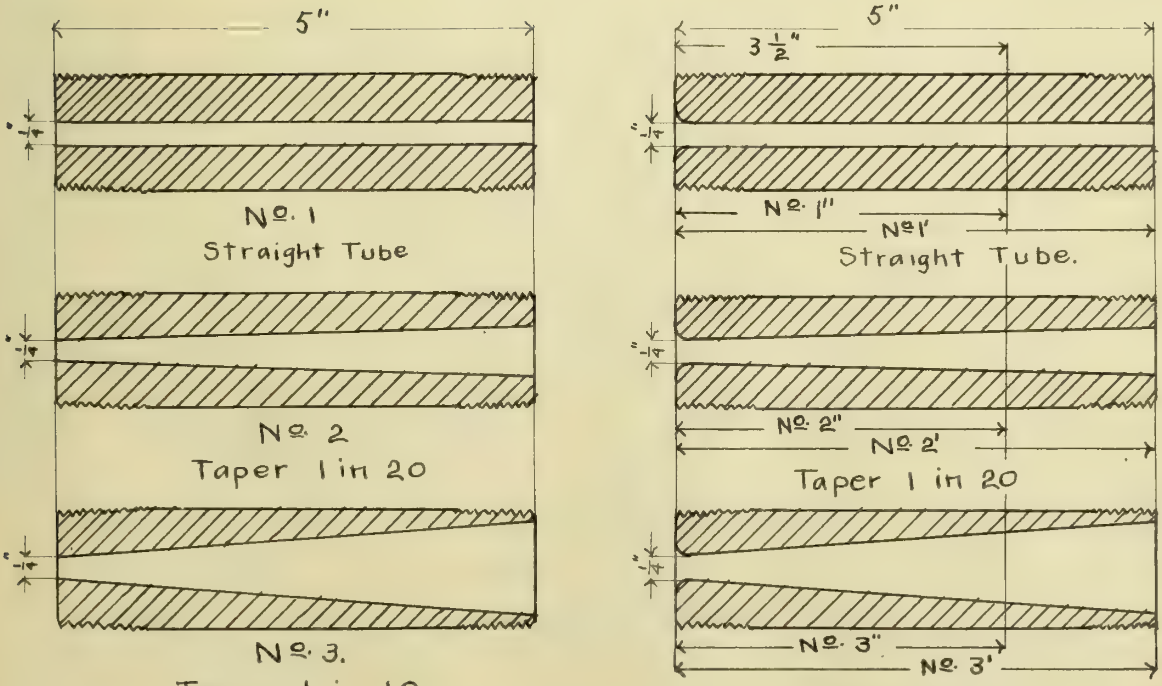
DIAGRAM SHOWING
ARRANGEMENT OF APPARATUS FOR MEASURING
THE IMPULSE OF THE JET.

which was supported on the scale, s, the impulse thus being measured directly. The pressure of steam in c was regulated by means of the gate valve b, the gage g, showing just what this pressure was. The impulse plate d, could be raised or lowered, and set at any desired distance from the end of the nozzle. It was set perpendicular to the axis of the nozzle by means of the leveling screws p.

A diagram showing the construction of receiver c, will be found on page 21 It will be seen that the steam inlet pipe extends some distance into the receiver, and has a cap on its end. A number of $\frac{1}{4}$" holes are drilled in it at different places. This prevents the steam from rushing directly from the pipe into the nozzle, and equalizes the steam pressure in all parts of the receiver. The steam gage was connected at D. The nozzles were threaded and screwed in at F, care being taken to have them extend at least



Upper Receiver.



No. 1
Straight Tube

No. 2
Taper 1 in 20

No. 3.
Taper 1 in 10

No. 1"
No. 1'
Straight Tube.

No. 2"
No. 2'
Taper 1 in 20

No. 3"
No. 3'
Taper 1 in 10

Nozzles Tested.

$\frac{1}{4}$" into the receiver. A $\frac{1}{8}$" pipe led away from E, thru which steam flowed continually during each set. This served to drain the water which collected in the bottom of the receiver, and to keep the steam, which flowed thru the nozzle, dry. The steam gage used was graduated to read to 5 pounds, and was carefully calibrated before being used. The scales used were graduated to read to .02 pounds, and were also carefully calibrated.

The method followed in each experiment was as follows: The impulse plate was first set perpendicular to the axis of the nozzle, and at the desired distance from it. The scales were then carefully balanced. The steam was then turned on, and the pressure in the receiver allowed to reach the maximum desired, which was in most cases 120 pounds. It was allowed to remain at this pressure for several minutes, until the apparatus was thoroughly warmed up, after which the scales

were balanced and the reading taken. The valve b, was then closed just enough to cause the steam pressure in the receiver to fall ten pounds. As soon as the pressure became steady, another reading was taken. Thus a reading was taken for each ten pounds from the maximum to the minimum desired. The pressure was always decreased from one reading to the next, as this tended to keep the steam dry. Some trouble was experienced from water collecting on the scales, and it was found necessary to keep this carefully wiped off. In other respects the apparatus worked satisfactorily, and the results obtained are supposed to be fairly accurate.

2.

Apparatus and Method for Determining the Mass of Steam Discharged.

A diagram showing the arrangement of the apparatus used for determining the mass of steam dis-

charged, will be found on page 25 The same receiver, c, was used as in determining the impulse of the jet. On the lower end of the nozzle was screwed the bottom cylindrical receiver d. A compound gage, g', was connected to d, as shown in the figure, so as to give the pressure in d. From the lower end of d, a 2" pipe led to the condenser used, which was a Wheeler Surface Condenser. In this 2" pipe near the receiver d, was a throttle valve, f. At k, the steam, now condensed, left the condenser, and was forced by the wet air pump into the tank t, which rested on the same scales which were used in determining the impulse of the steam.

The method used was as follows: The condenser pump was first started, and the throttle valve f opened wide. The valve b was then opened, admitting steam to c up to the maximum pressure used. The steam now was discharging from c into d, against

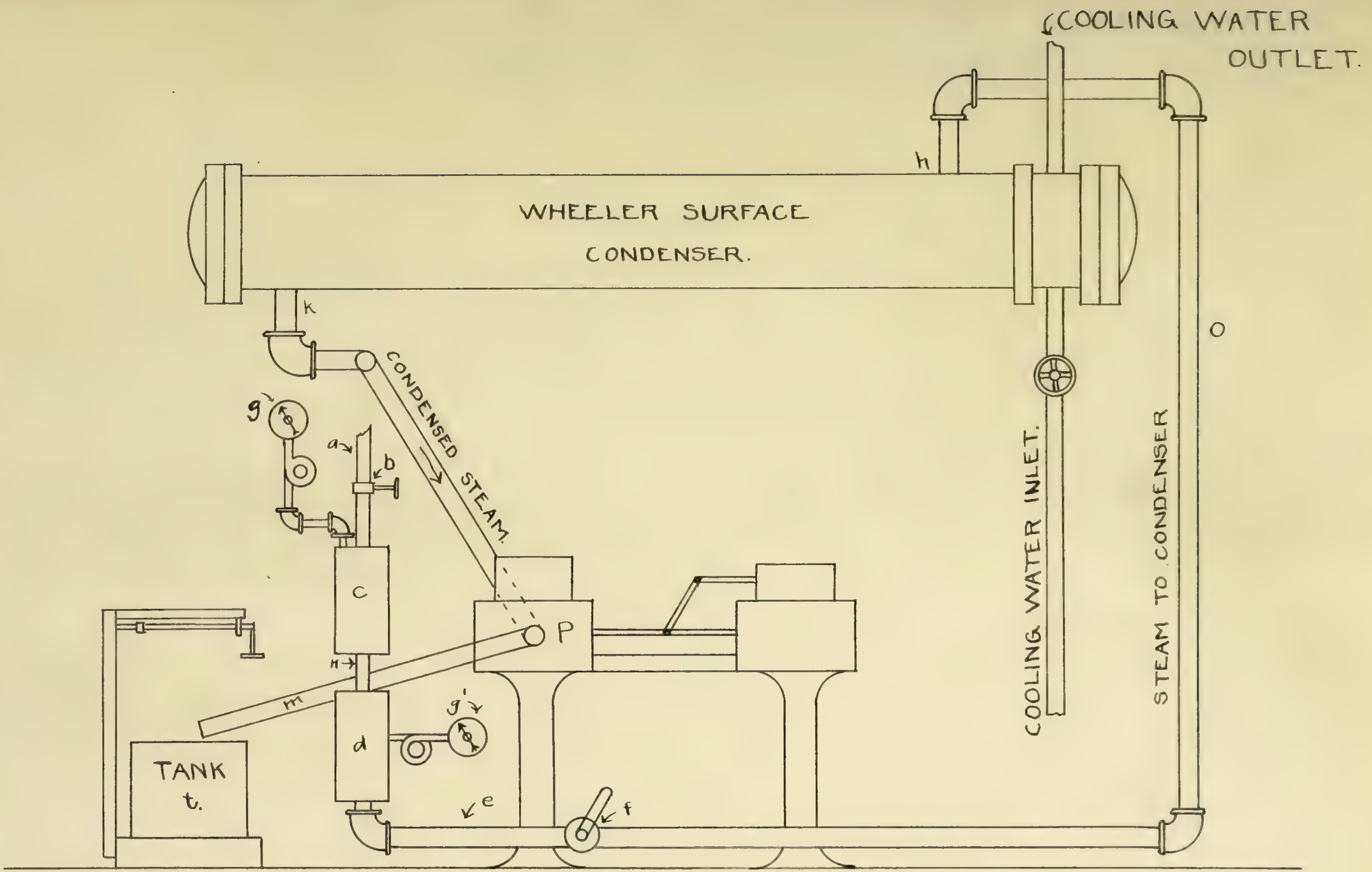


DIAGRAM SHOWING
ARRANGEMENT OF APPARATUS FOR MEASURING
THE MASS OF STEAM DISCHARGED.

some pressure less than atmospheric. The throttle valve f, was then gradually closed until the compound gage g', read just 0. The steam was then being discharged against atmospheric pressure. It was allowed to run for several minutes, until a state of stability was reached. Meanwhile, the scales on which rested the empty tank, t, were balanced. Then at some definite time, which was carefully noted, the pipe m, which up till this time had been discharging to waste, was turned so that it discharged into tank t. Both pressures in c and d, were then kept constant until an interval of 15 minutes had passed, when the pipe m, was again turned so that it discharged to waste. The water which had collected in t was then weighed. This weight was divided by the number of seconds in 15 minutes (900) The result being the weight of steam discharged per second. This process was

repeated for a steam pressure corresponding to the next ten pounds lower, and so on to the minimum pressure desired.

It was found necessary to wait some little time after the steam was first turned on in order to be sure that a condition of stability had been reached. Otherwise the weight discharged was entirely too large. This was accounted for by the supposition that, when the steam was first turned on, or when the pressure was raised, water which had collected in the pipe e, and the upright O, (see page 25) was carried over into the condenser, and on into the tank, t, thus giving a larger weight than had actually passed thru the nozzle. When precautions were taken against this error, the results seemed to be fairly uniform.

Before any tests were made, the condenser was run without any steam being admitted to it, but with the cooling water flowing thru it,

and it was noticed whether any water was delivered by the air pump. This was done to make sure that there were no leaks in the condenser.

V

The Nozzles Tested.

Diagrams of the nozzles which were tested will be found on page 21. They were made of brass, and were carefully prepared to exact dimentions.

No. 1 is simply a straight tube, $\frac{1}{4}$" in diameter and 5" long, with a sharp inner edge.

No. 1' is the same as no. 1, with the inner edge rounded.

No. 1" is the same as no. 1', but is only $3\frac{1}{2}$" long.

No. 2, has a taper of 1 in 20, is 5" long, $\frac{1}{4}$" in diameter at the small end, and has a sharp inner edge.

No. 2' is the same as no. 2 with the inner edge rounded.

No. 2" is the same as no. 2', but only $3\frac{1}{2}$" long.

No. 3 has a taper of 1 in 10, is 5" long, $\frac{1}{4}$" in diameter at the small end, and has a sharp inner edge.

No. 3' is the same as no. 3, with the inner edge rounded.

No. 3'' is the same as no. 3', but is only 3 $\frac{1}{2}$'' long.

VI
Conclusion.

Tables showing the results obtained will be found on pages 35 to 44. In the tables marked "Impulse", each reading given is the average of two readings which are not recorded. As an examination of the tables marked "Velocity" will show, two velocities were calculated for each nozzle, as follows: (1) The velocity near the end of the nozzle, generally $\frac{1}{4}$" from it, where the impulse was a minimum, and (2) the velocity at the point where the impulse was a maximum. This was at $2\frac{1}{2}$" from the end of the nozzle in most cases, but with nozzles #1', #3 and #3', it was at 2", and with #2', it was at at 1" from the end of the nozzle. Thus, practically the minimum and maximum velocities of the steam after it leaves the end of the nozzles, are recorded in each case. The formula given on page 15 was used, as stated there, in

calculating all velocities.

Curves were plotted for each nozzle having the steam pressures in pounds per square inch as abscissae, and the following quantities as ordinates: (1) The impulse in pounds; (2) The discharge in pounds per second; and (3) The velocity in feet per second. These will be found on pages 44 to 51.

An examination of the steam pressure — impulse curves (see pages 44, 45 and 46), will show the following points. Of nozzles #1, #2 and #3, with the square inner edge, #1 gave the greatest impulse, #2 the next, and #3 the least. However it will be noticed that curves 2 and 3 have a greater slope than 1, so that if they were continued they would cross 1. This seems to show that if much higher pressures were used, the nozzles #2 and #3 would give a greater impulse than #1. When the inner edges were rounded, thus admitting more steam, the impulse with nozzle #1 was greater than the

others only at the lower pressures. (see page 45.). At the higher pressures nozzle #2' gives the greatest and #1' the least. This same thing is shown in a more marked degree by the curves on page 46, which shows the effect of shortening the nozzles. This all seems to show, that of the nozzles with the square inner edge both #2 and #3 are too long, and have too much taper, thus allowing the steam to expand to the lower pressure somewhere back in the nozzle, instead of just at the mouth, as it should. When the inner edges were rounded, more steam was discharged, but evidently nozzle #3 still had too much taper, even at the highest pressures reached.

It will be seen by examining the curves on pages 47 and 48, that the greatest discharge was given in each case by the nozzle with the large taper (1 in 10) altho there was very little difference between that and the one with the taper 1 in 20. The straight tube,

however, plainly gave the least discharge in every case except at some of the lower pressures.

An examination of some of the steam pressure — velocity curves, (pages 49, 50 and 51) will show that the highest velocity was given by the straight tube in every case except in the case of the shorter nozzles, when the nozzle with the taper 1 in 20, gave the highest velocity. One rather interesting point which is shown plainly on page 50, is that, with the straight tube the velocity decreases very slowly as the steam pressure is lowered, while with the taper nozzles it decreases much more rapidly.

Thus these experiments show that for steam pressures above 90# gage, the nozzle with the taper 1 in 20 and 3½" long, with the rounded inner edge, gave the best results of any tested. For pressures below 90# a tube of less taper, or even a straight tube, is evidently better.

NOZZLE No. 1.

IMPULSE.

Steam Pressure Lbs. per Sq. In.	Impulse at Distance From End of Nozzle Shown.						
	13/32"	1"	2"	2 1/2"	3"	4"	5"
110	5.23	5.45	5.56	5.61	5.52	5.60	5.53
100	4.79	4.99	5.03	5.08	5.02	5.09	5.00
90	4.32	4.45	4.56	4.60	4.50	4.63	4.57
80	3.75	3.90	3.97	4.05	3.92	4.11	4.05
70	3.26	3.42	3.47	3.48	3.42	3.53	3.50
60	2.72	2.90	2.88	2.90	2.94	3.00	3.04
50	2.15	2.34	2.46	2.42	2.30	2.55	2.47
40	1.66	1.92	1.96	1.91	1.83	2.02	2.08
30	1.13	1.36	1.36	1.37	1.31	1.51	1.46
20	0.70	0.80	0.78	0.82	0.69	0.92	0.93
10	0.33	0.34	0.36	0.35	0.23	0.38	0.43

VELOCITY.

Steam Pressure Lbs. per sq. in.	Impulse at 13/32" from end of Nozzle. Lbs.	Impulse at 2 1/2" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of steam Discharged per Sec. Lbs	Velocity at 2 1/2" from end of Nozzle ft/sec.	Velocity at 13/32" from end of Nozzle. ft/sec.
110	5.23	5.61	61.29	.0681	2649	2460
100	4.79	5.08	58.50	.0650	2513	2370
90	4.32	4.60	53.92	.0599	2470	2319
80	3.75	4.05	49.27	.0547	2380	2206
70	3.26	3.48	42.68	.0474	2360	2212
60	2.72	2.90	37.20	.0413	2257	2115
50	2.15	2.42	32.68	.0363	2142	1804
40	1.66	1.91	28.61	.0318	1930	1680
30	1.13	1.37	22.65	.0252	1749	1444
20	0.70	0.82	17.51	.0195	1310	1150
10	0.33	0.35	9.45	.0105	1070	1010

NOZZLE No. 2.

IMPULSE.

Steam Pressure. Lbs. per sq. in.	Impulse at Distance From End of Nozzle Shown.						
	1/4"	1"	2"	2 1/2"	3"	4"	5"
120	5.07	5.38	5.46	5.53	5.45	5.29	5.38
110	4.63	4.87	5.02	5.04	4.91	4.77	4.87
100	4.07	4.27	4.40	4.36	4.34	4.23	4.36
90	3.49	3.72	3.79	3.79	2.76	3.65	3.73
80	2.89	3.08	3.22	3.21	3.17	3.05	3.16
70	2.33	2.55	2.63	2.62	2.59	2.50	2.59
60	1.83	1.98	2.11	2.10	2.07	1.01	2.07
50	1.33	1.50	1.60	1.68	1.51	1.46	1.53
40	0.98	1.04	1.11	1.14	1.08	1.03	1.16
30	0.58	0.57	0.64	0.66	0.60	0.55	0.70
20	0.34	0.33	0.39	0.38	0.34	0.30	0.43
10	0.21	0.20	0.25	0.26	0.20	0.17	0.29

VELOCITY.

Steam Pressure. Lbs. per Sq. in.	Impulse at 2 1/2" from end of Nozzle. Lbs.	Impulse at 1/4" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs	Wt. of Steam Discharged per sec. Lbs	Velocity at 2 1/2" from end of Nozzle. ft/sec	Velocity at 1/4" from end of Nozzle. ft/sec.
120	5.53	5.07	69.78	.0775	2300	2105
110	5.04	4.63	65.56	.0728	2230	2045
100	4.36	4.07	58.98	.0655	2140	2000
90	3.79	3.49	51.69	.0574	2120	1950
80	3.21	2.89	47.99	.0533	1935	1740
70	2.62	2.33	43.22	.0480	1755	1560
60	2.10	1.83	38.08	.0423	1590	1390
50	1.68	1.33	33.14	.0368	1466	1160
40	1.14	0.98	26.76	.0297	1235	1060
30	0.66	0.58	21.68	.0241	880	775
20	0.38	0.34	14.54	.0162	755	675
10	0.26	0.21	11.42	.0127	657	531

NOZZLE No. 3

IMPULSE.

Steam Pressure. Lbs. per sq. in.	Impulse at Distance From End of Nozzle Shown						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5"
120	3.86	—	5.05	4.88	5.03	4.77	4.62
110	3.36	4.44	4.58	4.23	4.51	4.14	4.06
100	2.68	3.89	4.01	3.69	3.89	3.51	3.47
90	2.26	3.33	3.41	3.04	3.35	2.94	2.86
80	1.80	2.69	2.80	2.46	2.65	2.34	2.28
70	1.38	2.14	2.26	1.94	2.16	1.83	1.80
60	1.03	1.69	1.73	1.48	1.71	1.30	1.32
50	0.75	1.30	1.34	0.99	1.31	0.93	0.90
40	0.56	1.02	1.03	0.72	0.97	0.66	0.65
30	0.42	0.77	0.83	0.47	0.76	0.42	0.44
20	0.24	0.62	0.67	0.36	0.63	0.31	0.31
10	0.15	0.54	0.61	0.27	0.56	0.23	0.23.

VELOCITY.

Steam Pressure Lbs. per sq. in.	Impulse at 2" from end of Nozzle. Lbs.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of steam Discharged per sec. Lbs.	Velocity at 2" from end of Nozzle. ft/sec.	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec.
120	5.05	3.86	70.57	.0784	2070	1585
110	4.58	3.36	66.15	.0735	2007	1470
100	4.01	2.68	60.90	.0677	1905	1275
90	3.41	2.26	54.50	.0606	1808	1200
80	2.80	1.80	49.72	.0552	1633	1048
70	2.26	1.38	45.29	.0503	1443	882
60	1.73	1.03	41.91	.0465	1195	713
50	1.34	0.75	33.77	.0375	1150	643
40	1.03	0.56	31.59	.0351	943	513
30	0.83	0.42	26.12	.0290	920	465
20	0.67	0.24	17.94	.0199	1080	388
10	0.61	0.15	14.02	.0155	—.	—

NOZZLE No 1"

IMPULSE.

Steam Pressure Lbs. per Sq. in.	Impulse at Distance From End of Nozzle Shown.						
	¼"	1"	2"	2½"	3"	4"	5"
120	7.00	7.26	7.59	7.59	7.33	7.23	7.12
110	6.40	6.71	7.05	7.06	6.78	6.75	6.58
100	5.80	6.09	6.49	6.51	6.11	6.11	5.96
90	5.17	5.44	5.79	5.85	5.50	5.49	5.40
80	4.65	4.82	5.18	5.13	4.89	4.91	4.92
70	4.00	4.27	4.47	4.64	4.27	4.29	4.25
60	3.37	3.61	3.88	3.95	3.61	3.68	3.72
50	2.81	2.95	3.28	3.33	2.99	3.13	3.17
40	2.32	2.48	2.75	2.85	2.49	2.58	2.58
30	1.68	1.89	2.11	2.19	1.83	1.97	1.91
20	1.06	1.23	1.43	1.56	1.13	1.21	1.28
10	0.54	0.63	0.75	0.84	0.47	0.57	0.66

VELOCITY.

Steam Pressure Lbs. per Sq. in.	Impulse at ¼" from end of Nozzle. Lbs	Impulse at 2½" from end of Nozzle. Lbs	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of Steam Discharged per sec. Lbs.	Velocity at 2½" from end of Nozzle. ft/sec.	Velocity at ¼" from end of Nozzle. ft/sec.
120	7.00	7.59	91.33	.1015	2400	2220
110	6.40	7.06	81.10	.0901	2520	2380
100	5.80	6.51	78.66	.0874	2395	2140
90	5.17	5.85	73.56	.0817	2300	2040
80	4.65	5.13	63.72	.0708	2330	2110
70	4.00	4.64	59.64	.0663	2250	1970
60	3.37	3.95	47.52	.0528	2410	2050
50	2.81	3.33	39.72	.0441	2420	2050
40	2.32	2.85	36.09	.0401	2280	1860
30	1.68	2.19	28.98	.0322	2190	1680
20	1.06	1.56	21.06	.0233	2150	1465
10	0.54	0.84	13.92	.0155	1740	1120

NOZZLE No 2"

IMPULSE.

Steam Pressure. Lbs. per Sq. in.	Impulse at Distance From End of Nozzle Shown.						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5"
120	8.07	8.60	8.80	8.93	8.84	8,76	8.66
110	7,45	7,85	8.13	8.18	8.00	7,98	7,88
100	6.66	7,09	7,35	7,35	7,22	7,17	7,05
90	5.85	6,37	6.46	6.60	6,29	6,33	6,20
80	5,14	5.48	5.63	5.69	5.36	5,56	5.44
70	4.44	4,75	4,91	4,97	4,66	4,74	4.69
60	3,57	4,13	4.16	4,23	3,97	4.04	3,91
50	2.81	3.36	3.31	3.47	3,19	3,23	3,22
40	2.38	2.62	2.69	2.72	2.60	2.55	2.62
30	1.65	1,81	2.03	1,92	1,70	1,76	1,70
20	0.97	1,19	1,18	1,21	0,95	0.97	0,93
10	0.66	0,77	0.73	0,80	0,59	0.60	0.60

VELOCITY.

Steam Pressure. Lbs. per sq. in.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs.	Impulse at $2\frac{1}{2}$" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of Steam Discharged per sec. Lbs.	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec.	Velocity at $2\frac{1}{2}$" from end of Nozzle. Lbs.
120	8.07	8.93	97.74	.1086	2420	2650
110	7,45	8.18	87.70	,0974	2460	2700
100	6,66	7.35	77.28	.0859	2500	2750
90	5.85	6.60	73.68	,0819	2300	2590
80	5.14	5.69	67.12	.0746	2210	2450
70	4.44	4,97	57,06	,0634	2250	2520
60	3,57	4.23	49.08	,0545	2110	2500
50	2.81	3,47	41.43	,0460	1965	2430
40	2.38	2,72	38.43	,0427	1800	2050
30	1.65	1.92	29.46	,0327	1620	1880
20	0,97	1, 21	21.42	,0238	1310	1635
10	0.66	0,80	13.29	.0148	1430	1740

NOZZLE Nº 3"

IMPULSE.

Steam Pressure Lbs. per Sq. in.	Impulse at Distance From End of Nozzle Shown.						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5".
120	7.24	7.82	7.96	7.96	7.81	7.59	7.71
110	6.34	7.06	7.18	7.21	7.06	6.82	6.92
100	5.52	6.21	6.40	6.43	6.25	5.99	6.18
90	4.87	5.51	5.60	5.61	5.44	5.13	5.32
80	3.97	4.73	4.82	4.89	4.64	4.62	4.63
70	3.01	3.93	3.95	4.02	3.79	3.63	3.74
60	2.45	3.16	3.20	3.24	2.99	2.92	3.00
50	1.74	2.54	2.59	2.55	2.24	2.28	2.21
40	1.20	1.89	1.92	1.94	1.71	1.62	1.61
30	0.73	1.14	1.13	1.24	0.89	0.87	0.85
20	0.48	0.64	0.57	0.61	0.34	0.37	0.32
10	0.32	0.38	0.37	0.42	0.16	0.16	0.14

VELOCITY.

Steam Pressure. Lbs. per sq. in.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs	Impulse at $2\frac{1}{2}$" from end of Nozzle. Lbs	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of Steam Discharged per sec. Lbs.	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec	Velocity at $2\frac{1}{2}$" from end of Nozzle. ft/sec.
120	7.24	7.96	95.71	.1063	2180	2400
110	6.34	7.21	87.87	.0976	2090	2380
100	5.52	6.43	80.19	.0891	1990	2320
90	4.87	5.61	75.06	.0834	1875	2160
80	3.97	4.89	68.40	.0760	1680	2060
70	3.01	4.02	58.26	.0647	1500	1995
60	2.45	3.24	51.60	.0573	1375	1790
50	1.74	2.55	44.62	.0496	1130	1650
40	1.20	1.94	40.59	.0451	855	1380
30	0.73	1.24	31.17	.0346	659	930
20	0.48	0.61	21.96	.0244	633	805
10	0.32	0.42	15.99	.0178	578.	760

NOZZLE Nº 1'.

IMPULSE.

Steam Pressure Lbs. per sq. in.	Impulse at Distance From End of Nozzle Shown.						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5"
120	7.16	7.58	7.73	7.18	7.18	6.96	6.86
110	6.65	7.10	7.17	6.62	6.58	6.43	6.39
100	6.06	6.43	6.54	6.05	6.01	5.78	5.76
90	5.50	5.85	5.94	5.46	5.34	5.12	5.06
80	4.94	5.17	5.28	4.83	4.73	4.55	4.55
70	4.31	4.64	4.75	4.20	4.09	3.96	3.92
60	3.76	4.03	4.13	3.53	3.59	3.35	3.36
50	3.18	3.48	3.48	2.97	2.92	2.74	2.70
40	2.76	2.90	2.99	2.44	2.41	2.25	2.24
30	1.92	2.23	2.30	1.75	1.68	1.55	1.54
20	1.36	1.63	1.62	1.04	1.06	0.90	0.88
10	0.94	1.02	1.04	0.44	0.37	0.30	0.22

VELOCITY

Steam Pressure. Lbs. per sq. in.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs.	Impulse at 2" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of steam Discharged per sec. Lbs.	Velocity at 2" from end of Nozzle. ft/sec.	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec.
120	7.16	7.73	86.07	.0956	2650	2410
110	6.65	7.17	77.80	.0864	2670	2480
100	6.06	6.54	71.83	.0798	2630	2440
90	5.50	5.94	67.25	.0747	2560	2370
80	4.94	5.28	60.40	.0670	2540	2370
70	4.31	4.75	57.15	.0635	2405	2190
60	3.76	4.13	46.22	.0513	2590	2355
50	3.18	3.48	39.90	.0443	2510	2310
40	2.76	2.99	34.14	.0379	2540	2340
30	1.92	2.30	27.40	.0304	2435	2030
20	1.36	1.62	15.00	.0167	3120	2620
10	0.94	1.04	10.90	.0120	2790	2520

NOZZLE Nº. 2!

IMPULSE.

Steam Pressure Lbs. per sq. in.	Impulse at Distance From End of Nozzle Shown.						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5"
120	7.81	8.18	8.01	8.05	8.13	8.09	8.16
110	7.24	7.38	7.33	7.36	7.40	7.33	7.42
100	6.45	6.61	6.49	6.57	6.57	6.48	6.52
90	5.60	5.79	5.68	5.63	5.66	5.53	5.71
80	4.88	4.98	4.91	4.99	4.91	4.86	4.96
70	4.01	4.20	4.05	4.07	4.08	4.02	4.06
60	3.23	3.38	3.26	3.32	3.32	3.28	3.28
50	2.57	2.72	2.52	2.92	2.54	2.52	2.54
40	1.84	2.06	1.96	1.95	1.87	1.85	1.87
30	1.23	1.28	1.13	1.03	1.13	1.03	1.14
20	0.65	0.70	0.48	0.45	0.49	0.42	0.55
10	0.40	0.43	0.22	0.17	0.22	0.18	0.26

VELOCITY.

Steam Pressure. Lbs. per sq. in.	Impulse at 1" from end of Nozzle. Lbs.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs.	Wt. of Steam Discharged in 15 min. Lbs.	Wt. of steam Discharged per sec. Lbs.	Velocity at 1" from end of Nozzle. ft/sec.	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec.
120	8.18	7.81	92.17	.1024	2560	2450
110	7.38	7.24	84.33	.0930	2550	2500
100	6.61	6.45	79.77	.0886	2400	2340
90	5.79	5.60	70.56	.0784	2380	2300
80	4.98	4.88	64.98	.0722	2220	2175
70	4.20	4.01	57.62	.0640	2110	2010
60	3.38	3.23	52.57	.0584	1860	1780
50	2.72	2.57	44.82	.0498	1750	1660
40	2.06	1.84	37.18	.0413	1605	1430
30	1.28	1.23	30.12	.0335	1230	1180
20	0.70	0.65	21.66	.0241	935	867
10	0.43	0.40	15.06	.0167	828.	770

NOZZLE No. 3.

IMPULSE.

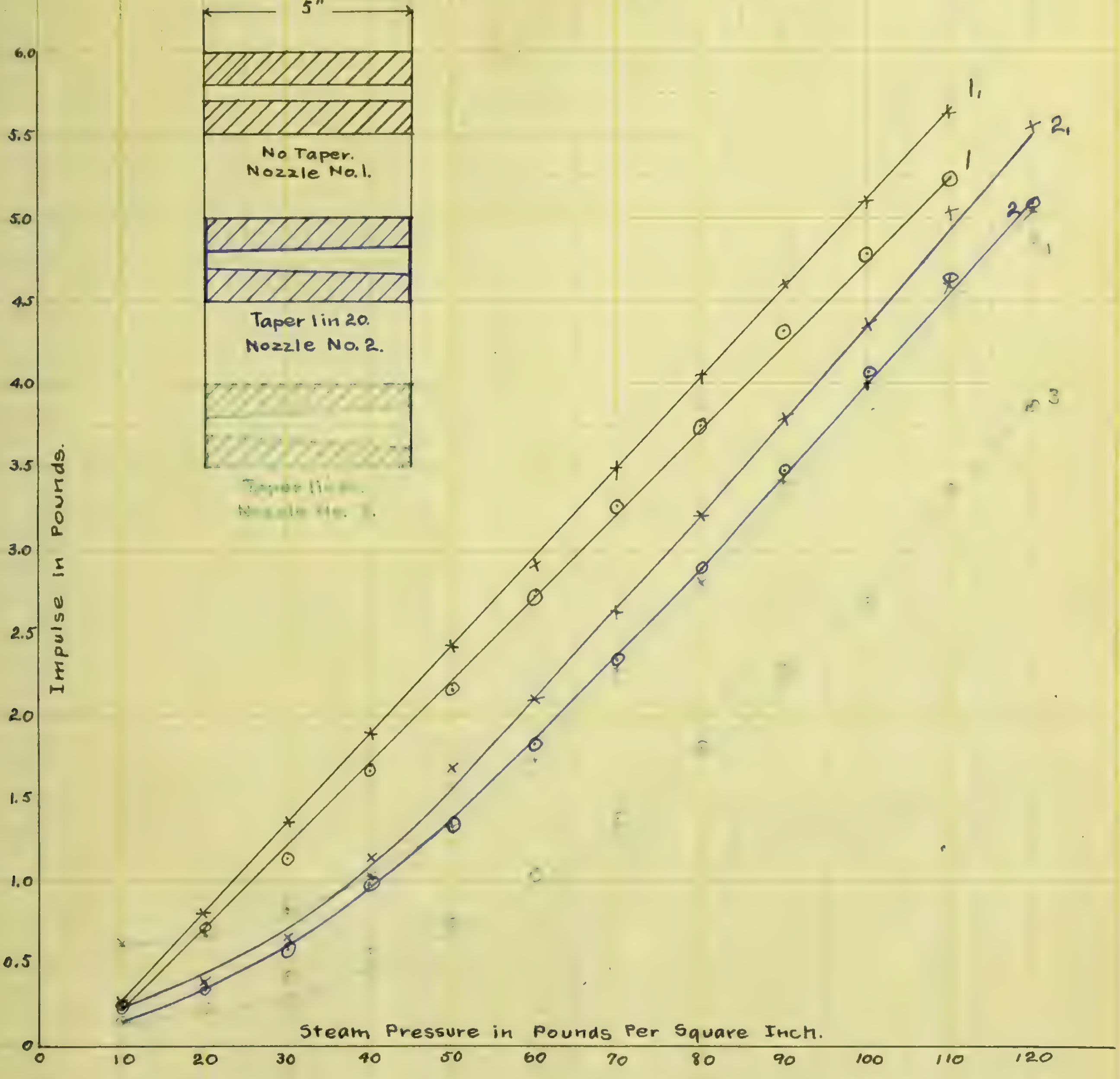
Steam Pressure. Lbs. per sq. in.	Impact at Distance From End of Nozzle Shown.						
	$\frac{1}{4}$"	1"	2"	$2\frac{1}{2}$"	3"	4"	5"
120	—	7.27	7.37	6.95	6.94	6.89	6.74
110	5.85	6.50	6.57	6.21	6.08	6.09	5.90
100	5.09	5.73	5.77	5.39	5.31	5.32	5.12
90	4.43	4.89	4.93	4.58	4.53	4.50	4.40
80	3.69	4.13	4.13	3.81	3.63	3.65	3.62
70	2.96	3.33	3.37	3.01	2.88	2.94	2.77
60	2.30	2.63	2.64	2.30	2.19	2.21	2.15
50	1.77	1.98	1.96	1.74	1.55	1.54	1.48
40	1.28	1.46	1.41	1.12	1.01	1.02	0.99
30	0.84	0.91	0.89	0.62	0.53	0.56	0.53
20	0.60	0.68	0.67	0.37	0.24	0.35	0.30
10	0.45	0.57	0.54	0.24	0.12		0.14

VELOCITY

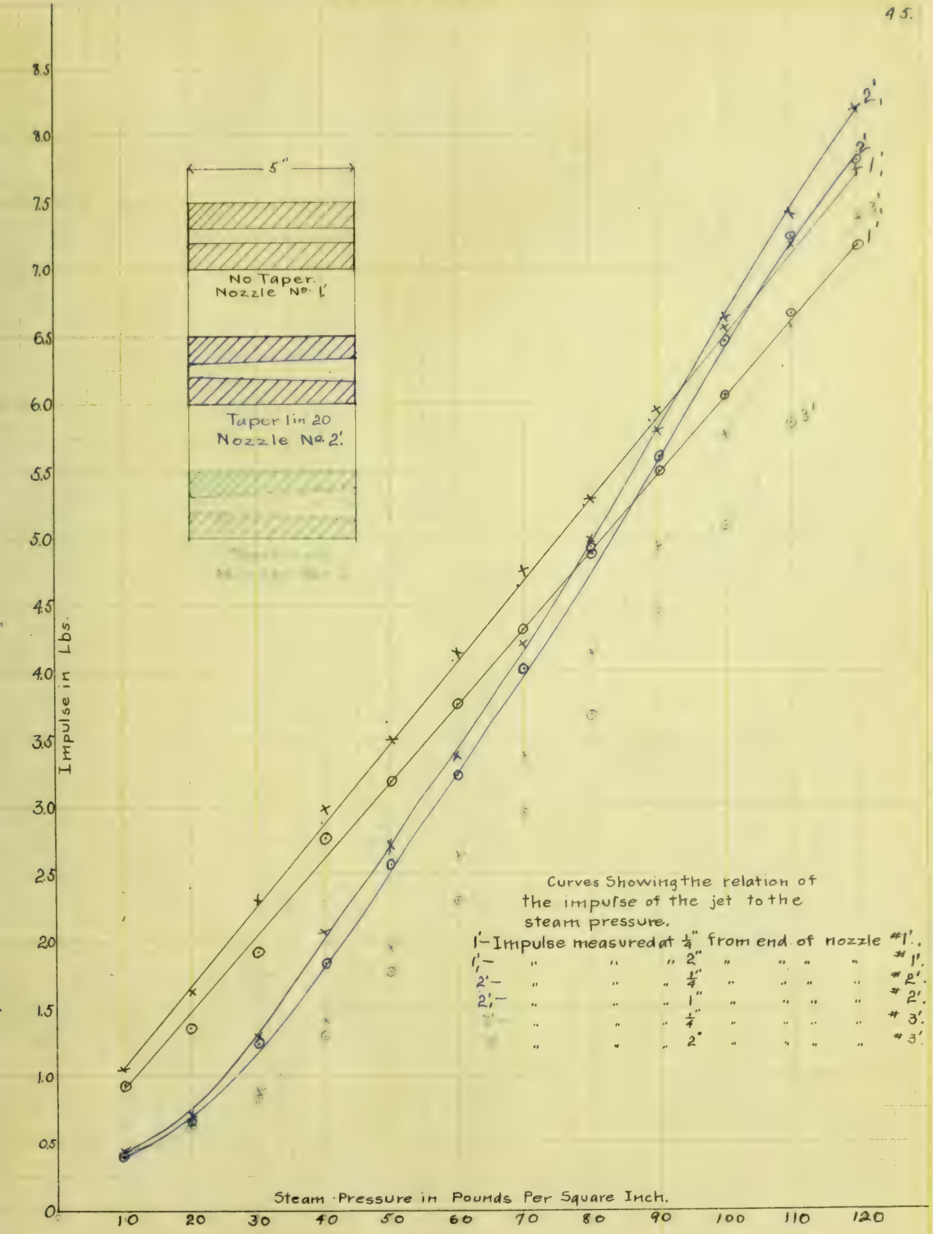
Steam Pressure Lbs. per sq. in.	Impulse at 2" from end of Nozzle. Lbs.	Impulse at $\frac{1}{4}$" from end of Nozzle. Lbs.	Wt. of steam Discharged in 15 min. Lbs.	Wt. of Steam Discharged per sec. Lbs.	Velocity at 2" from end of Nozzle. ft/sec	Velocity at $\frac{1}{4}$" from end of Nozzle. ft/sec.
120	7.37	—	—	—	—	—
110	6.57	5.85	86.57	.0962	2190	1960
100	5.77	5.09	77.64	.0863	2140	1900
90	4.93	4.43	71.28	.0792	2000	1800
80	4.13	3.69	67.14	.0746	1780	1590
70	3.37	2.96	59.27	.0658	1650	1445
60	2.64	2.30	50.82	.0565	1505	1310
50	1.96	1.77	45.62	.0507	1245	1123
40	1.41	1.28	38.54	.0428	1055	960
30	0.89	0.84	30.30	.0337	850	800
20	0.67	0.60	22.65	.0252	855	765
10	0.54	0.45	14.88	.0165	1050	875

Curves
Showing the relation
of the impulse of the jet.
to the steam pressure.

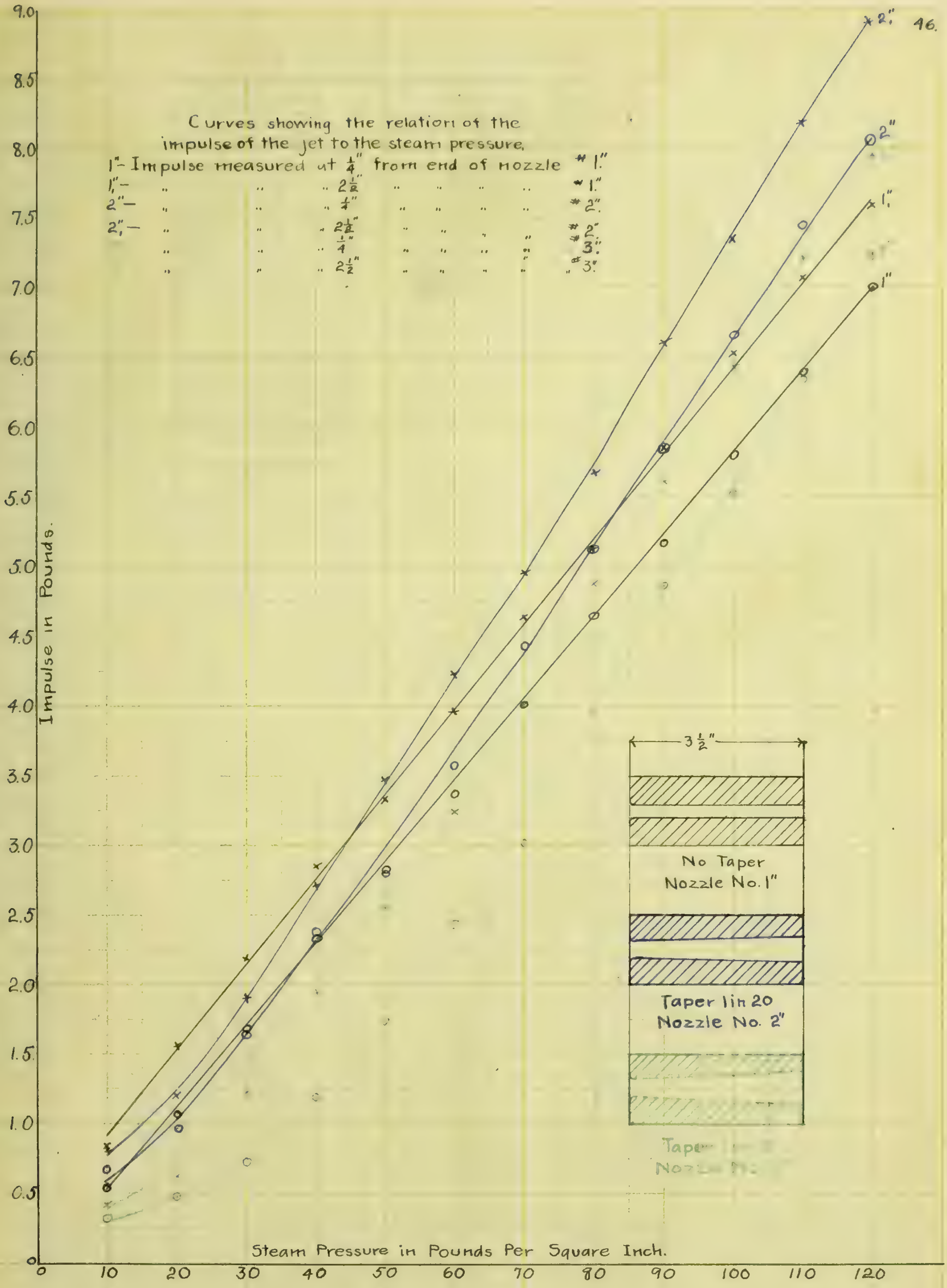
1—Impulse measured at $\frac{13}{32}$" from the end of nozzle #1.
1,— " " " $2\frac{1}{2}$" " " " " " #1.
2— " " " $\frac{1}{4}$" " " " " " #2.
2,— " " " $2\frac{1}{2}$" " " " " " #2.
3— " " " $\frac{1}{4}$" " " " " " #3.
3,— " " " 2" " " " " " #3.



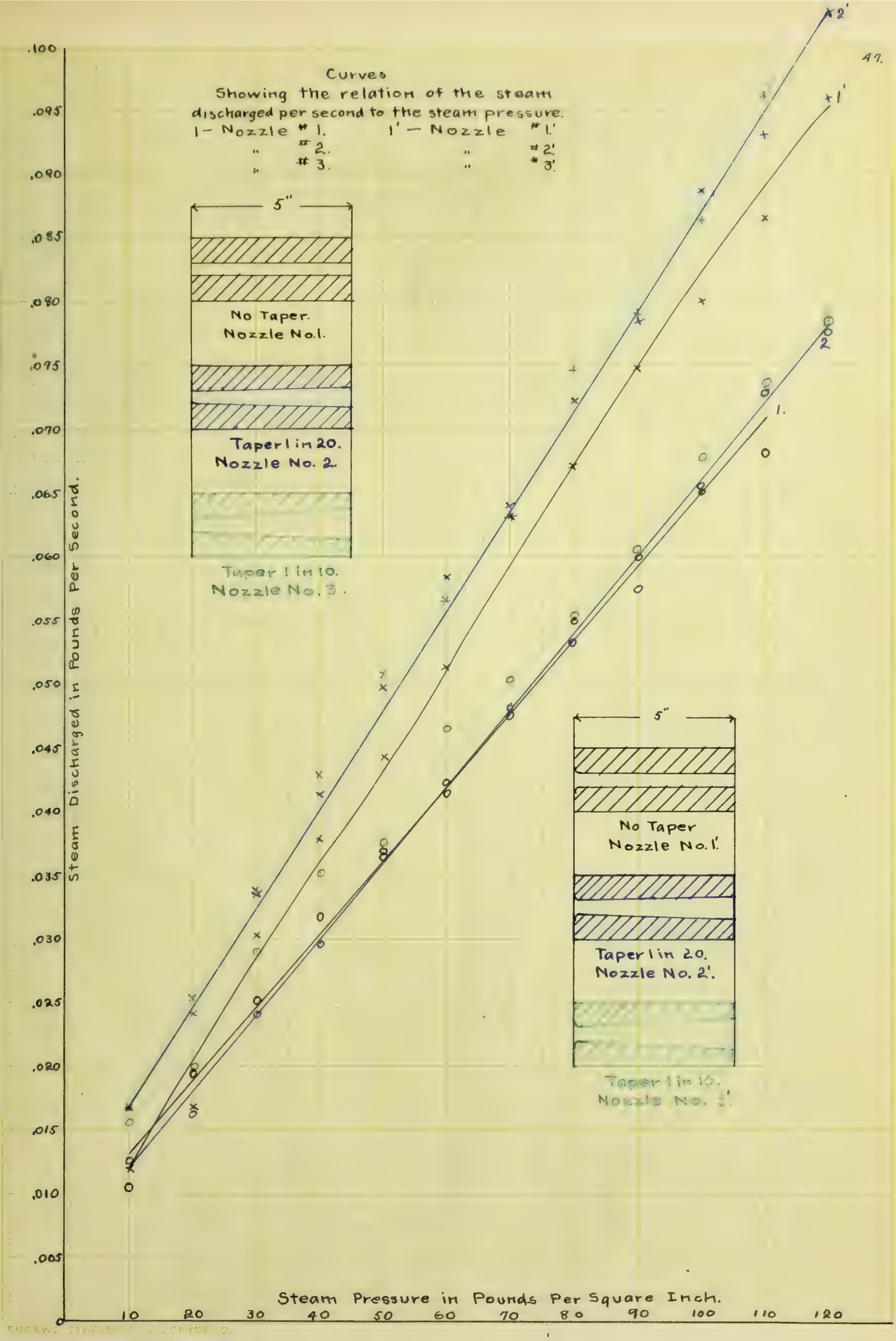
EUGENE DIETZGEN CO., CHICAGO.



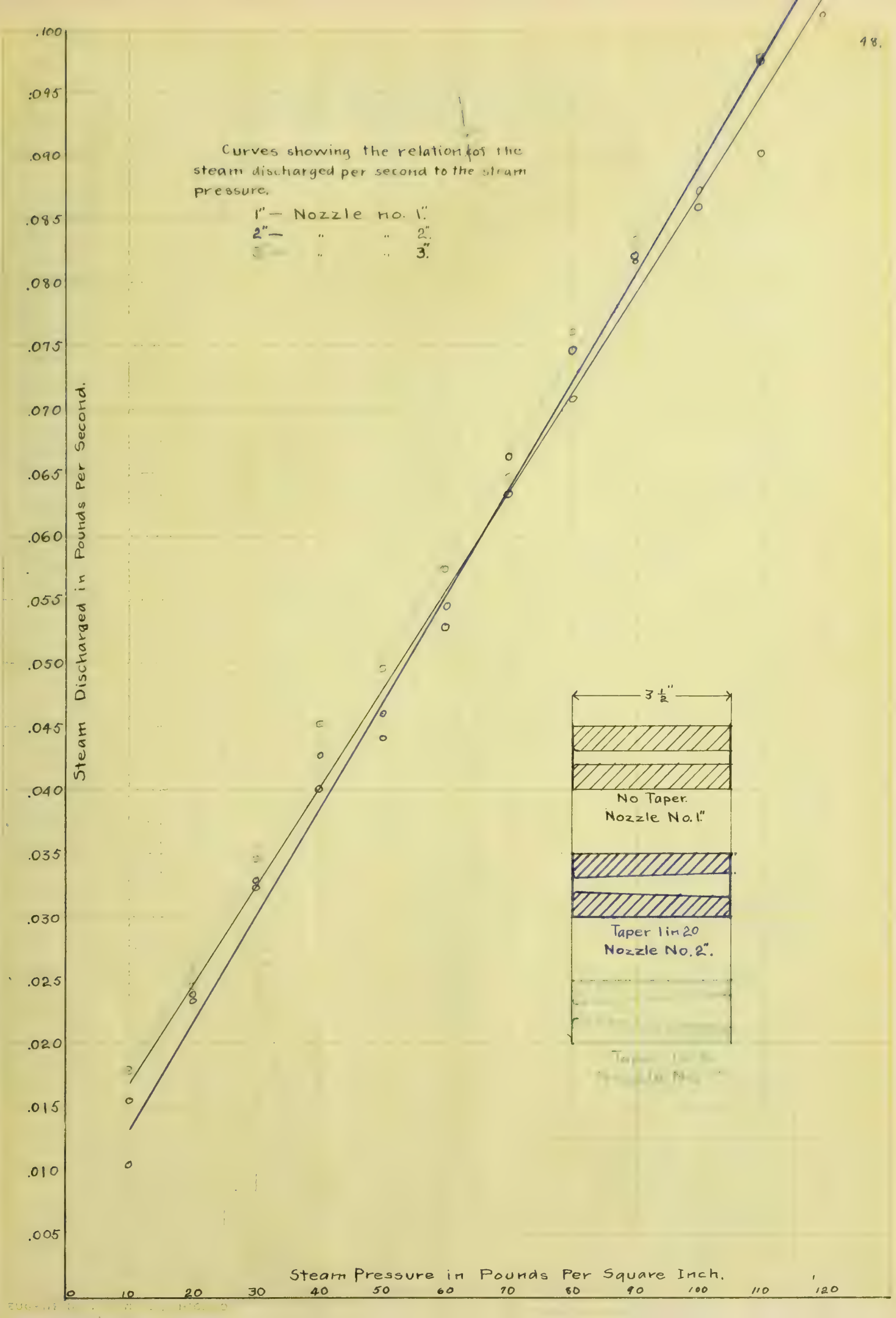
Curves Showing the relation of the impulse of the jet to the steam pressure.

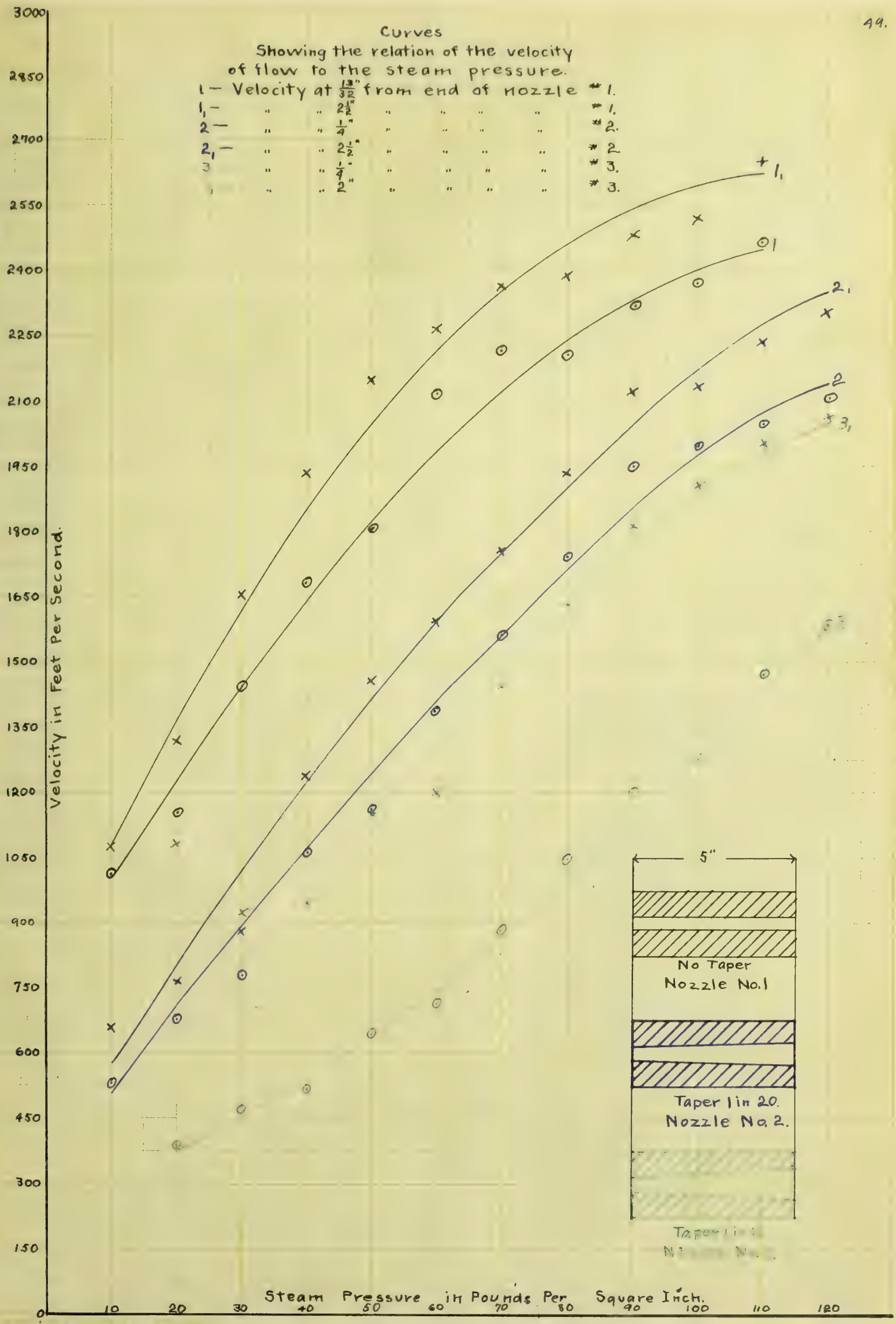


EUGENE DIETZGEN CO.,

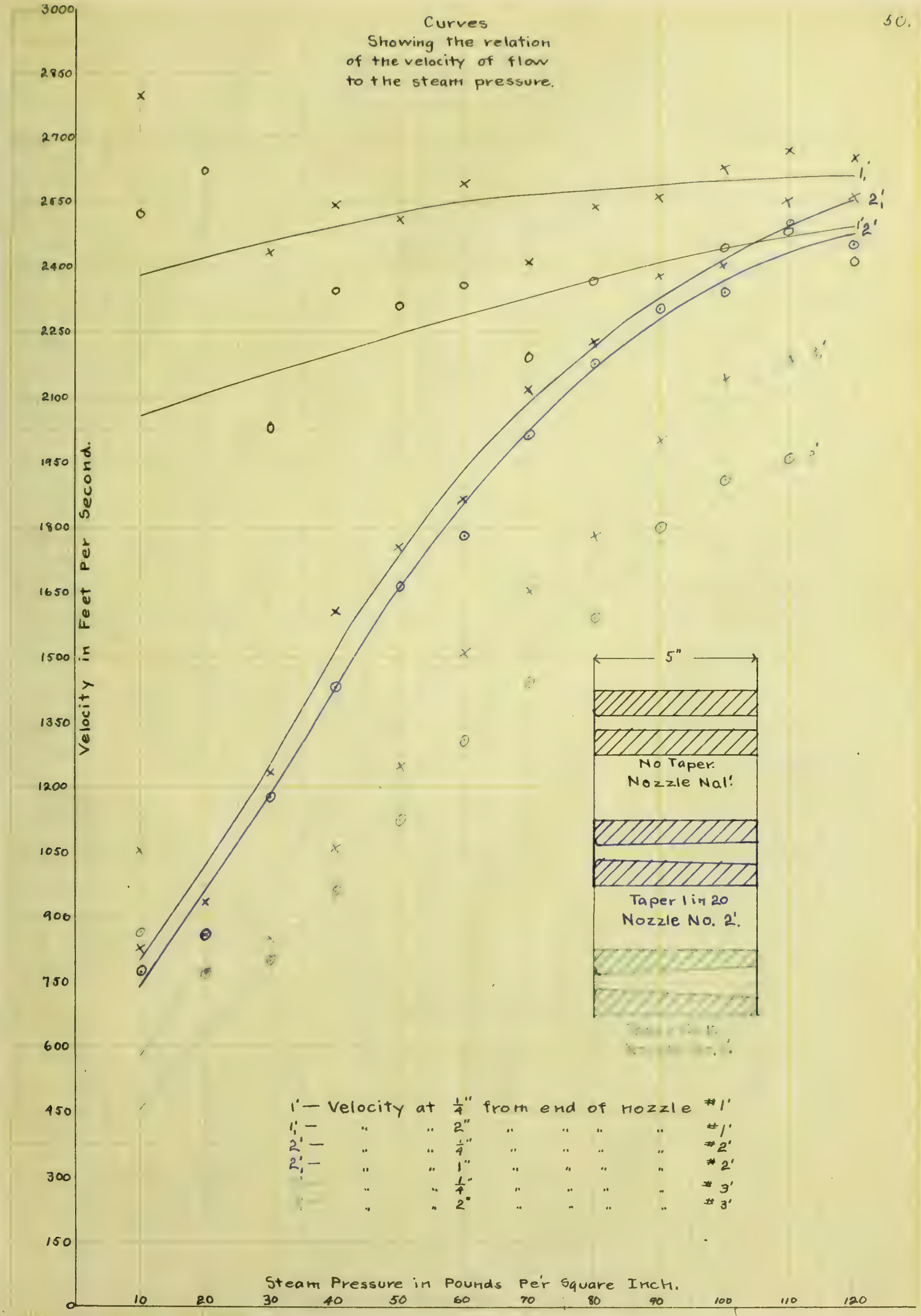


EUGENE DIETZGEN CO. CHICAGO

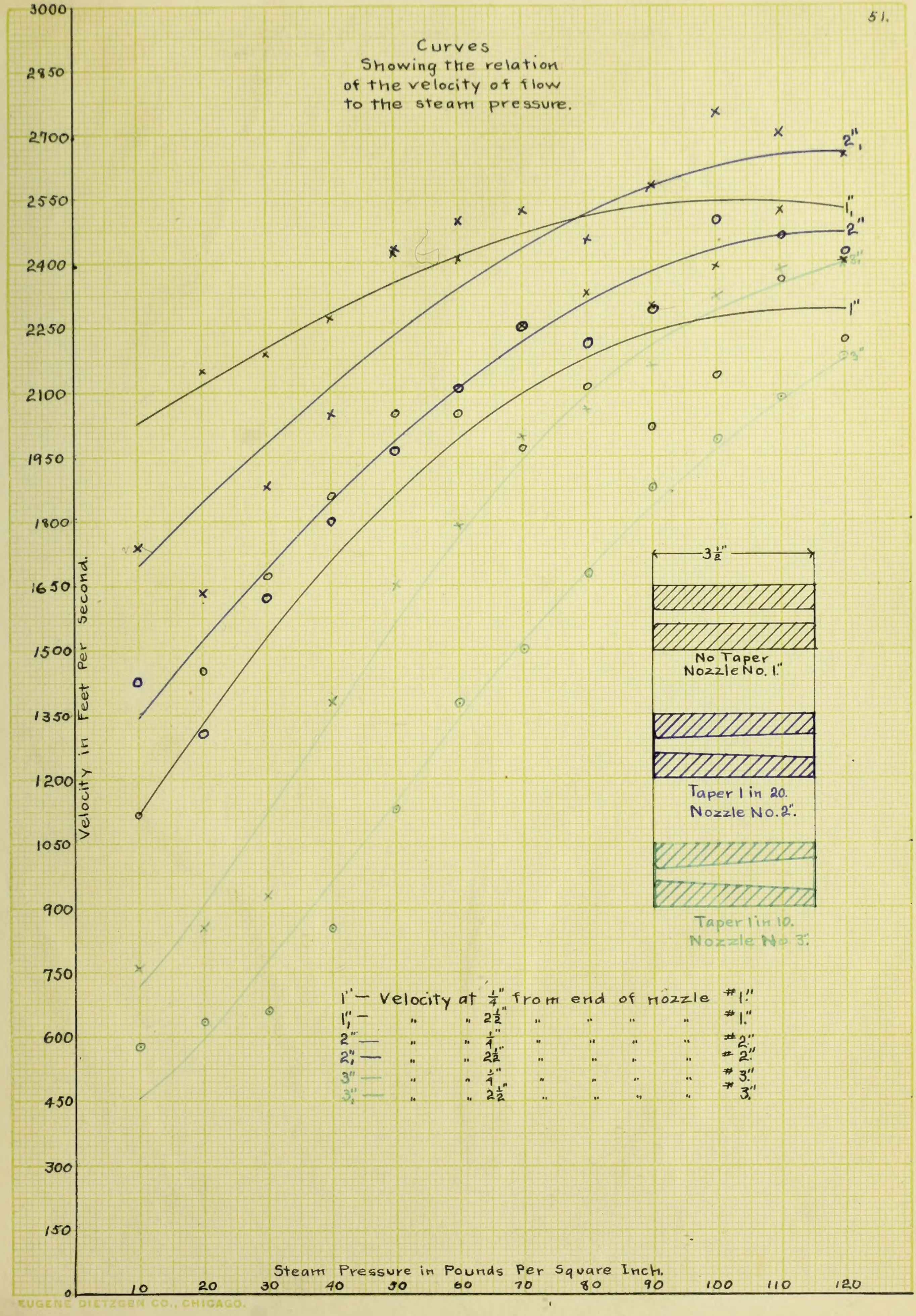

Curves showing the relation of the steam discharged per second to the steam pressure.
1" — Nozzle no. 1".
2" — " " 2".
3" — " " 3".
Steam Discharged in Pounds Per Second.
Steam Pressure in Pounds Per Square Inch.
.100
.095
.090
.085
.080
.075
.070
.065
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
10
20
30
40
50
60
70
80
90
100
110
120
3 1/2"
No Taper.
Nozzle No. 1".
Taper 1 in 20
Nozzle No. 2".



Curves
Showing the relation of the velocity
of flow to the steam pressure.



Curves
Showing the relation
of the velocity of flow
to the steam pressure.



Curves
Showing the relation
of the velocity of flow
to the steam pressure.

EUGENE DIETZGEN CO., CHICAGO.

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